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ORTHOPYROXENES FROM SUKINDA ULTRAMAFITES AND THE NATURE OF THE PARENTAL MAGMA

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ABSTRACT

Chromite-bearing ultramafites occur as synkinematic intrusions during the Eastern Ghat orogenic movement (2800—3000 m. y.), in Eastern India. The ultramafic instrusives are composed mainly of dunite, bronzitites, websterite and their metamorphic derivatives. These were emplaced by successive 'pulsation' intrusions and show some layered features.

Pure (>99,9%) orthopyroxenes separated from bronzitite, peridotite, websterite etc. were analysed by Philips automatic PW 1212 X-ray fluorescence spectrometer. The analyses revealed very low Al and Ca content compared to most other widely known localities of layered types. The En values (80—83%) are also lower than those of many alpine and stratiform complexes.

The crystallochemical considerations of the orthopyroxenes lead the author to assume a peridotite primary magma rather than a basic magma, occurring below the substratum in the Eastern Ghat region of E. India. To account for the crystallization of monomineralic rocks such as dunite, enstatitite, chromitites etc., liquids of these rock compositions are assumed to have been locally produced by partial fusion of peridotites. Absence of any literature in this direction leads the author to presume that Sukinda magma was compositionally unlike any of the presently known uppermantle magma genetic zones. The intrusive magma, however, might be contaminated during orogeny to change the path of crystallization.

INTRODUCTION

An ultramafic complex of Sukinda lying between Saruabil and Kolrangi (21°0′—21°5′ N:85°33′ E) occurs as syn-orogenic intrusions in the Iron Ore Series formations of the Eastern Ghat region. The intrusions took place during the Eastern Ghat Cycle 2800—3000 m.y. [SARKAR, 1968] ranging in the period Mesarchean to Katarchean [RAO, 1967].

The part of the complex studied covers an area of about 60 sq. miles and is composed mainly of perioditite, harzburgite, enstatite (with bronzitite), websterite, dunite, and their metamorphic equivalents, the details of which are treated elsewhere [MITRA, 1959, 1961]. The petrology and the mechanics of emplacement of the intrusives were first described by the author [1960] followed by CHATTERJEE and BANERJEE [1964]. The former considered the complex as a multiple intrusion with two major phases of intrusions of ultramafic magma, emplacing rocks and chromites from different horizons of a fractionated magma. The ultramafic intrusions were followed by basic and late acidic intrusions such as granophyre, granite etc. The latter are proved at depth by bore holes at the southwestern part of the map *(Fig. 1)*.

The ultrabasic intrusives trend NE—SW along the valley between the two quartzite ridges of Iron Ore Series, exposed in the north (the Daiteri range) and the south (the Mahagiri range) of the area (see the map, *Fig. 1*).

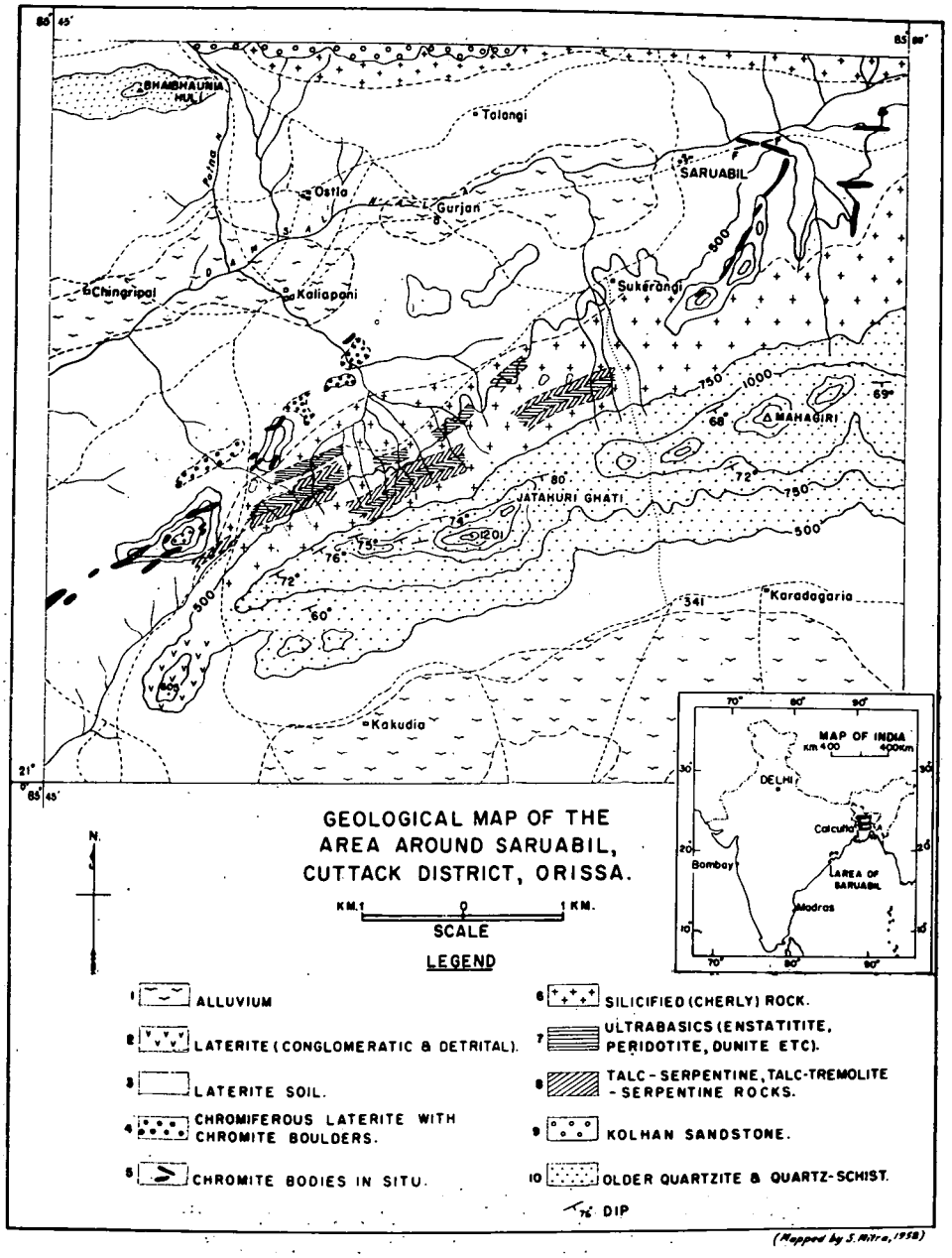

Fig. 1. Geological map of the Sukinda area around Saruabil and Tomka, Cuttack district, Orissa, India.

Fig. 2a. A photograph of a chromite quarry showing the layered nature.

The ultrabasic and the chromitites carry incipient to conspicuously layered structures formed by crystal settling and accumulation, also these are superimposed by tectonic layers. The earlier intrusive, exposed to-day exclusively as chromitite band at the village Saruabil (21°3′13″:85°35′) show such layering distinctly *(Fig. 2)*.

Extensive serpentinization, steatization and silicification removed all identifying traces of the ultramafic rocks associated with these chromite layers. At a later period intrusives of websterite, harzburgite, enstatitite, dunite and chromitite came up along the flanks of a syncline formed during Eastern Ghat Orogeny. Some of these rocks, occurring in the southern flank of the syncline are exposed near the

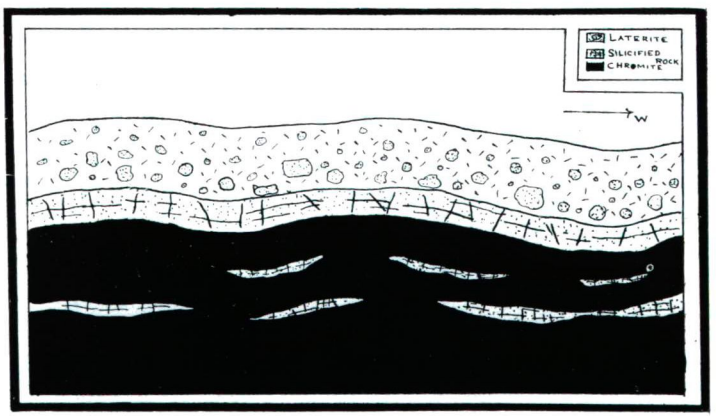

Fig. 2b. A diagrammatic representation of the E-W sectional view of the chromite lode of Q4 (S. C. M). The silicified bands of ultrabasic in chromite suggest its stratiform nature.

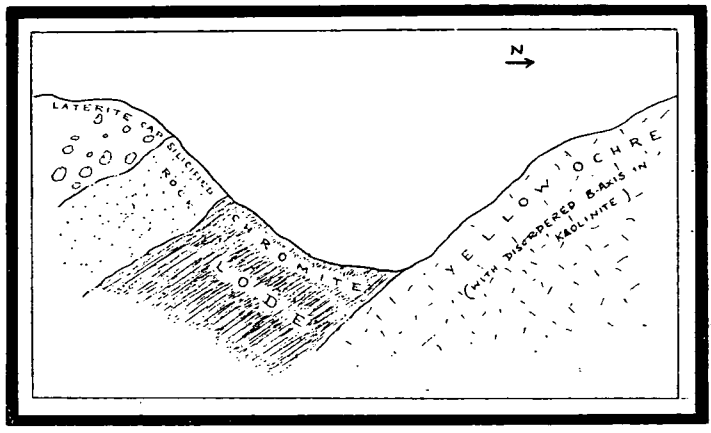

Fig. 2c. N-S section of the same as that of Fig. 2b.

foot-hills of the Mahagiri, which is found to be the zone of high pressure and shearing stress [MITRA, 1970].

Detailed petrographic and mineralogical investigations were carried out by the author since 1958 and individual mineralogical investigations have been taken up during the last four years to determine the mineralogical criteria for deciphering the nature of the present magma, and also to ascertain the process of crystallization and the mechanism of emplacement. In recent years, mineralogical criteria have been used in deciphering whether an intrusive is an Alpine Type or Stratiform Type [HESS, 1955, 1960; THAYER, 1960] or intermediate type having characters of both. Author's investigation on olivines from the present area [MITRA, 1970] indicated a magma of Alpine-type peridotite.

In the present paper the author has attempted to estimate the implications of the composition of orthopyroxenes of the enstatitites (bronzitites) and websterite collected from the southern part of the area.

MAJOR OXIDE ANALYSIS

Five samples of orthopyroxenes collected (hand picked under binocular microscope) from Sukinda enstatite and websterite were analyzed by using a Philips 1212 automatic X-ray Fluorescence Spectrometer. Major and trace elements were analyzed from prepared briquettes. (The counts were corrected for absorption and matrix by using the technique and computer programme of HOLLAND and BRINDLE, 1966*). The data are present in Table 1.

Calculations of the molecular percent of En [En = 100 Mg/Mg + Fe (total) + Mn] shows a variation from 80,38 to 83,30 (Table 2). The orthopyroxenes are biaxial positive and according to the nomenclature of DEER, HOWIE and ZUSSMAN [1963, 2, p. 9] these are enstatites. Some, however, place the boundary between enstatite

* All iron counts in the scintillation counter were originally calculated as Fe_2O_3 according ot the programme used. The Fe_2O_3 were calculated to FeO and the total was recalculated to proximate 100.

TABLE 1

Chemical analyses of orthopyroxenes from Sukinda ultramafites

Serial No.	1	2	3	4	5
Sample No.:	Ex	B124	B123	B68	M434
SiO_2	57.00	56.38	57.23	57.08	56.55
Al_2O_3	0.78	0.78	0.80	0.66	1.03
FeO	5.81	5.78	5.75	5.96	6.60
MgO	35.73	36.57	35.54	35.75	34.96
CaO	0.65	0.43	0.64	0.49	0.77
Na_2O	0.001	trace	0.01	0.04	0.02
K_2O	0.03	0.03	0.03	0.03	0.07
TiO_2	trace	0.03	0.03	0.03	0.001

and bronzite at En_{90} Fs_{10} [POLDERVAART, 1974]. According to that, therefore, these orthopyroxenes (En 80—83 Fs 20—17) from Sukinda are bronzite. In Table 6, these orthopyroxenes are compared with those from other areas with respect to their En values.

The compositions of these pyroxenes are studied in the light of the atomic and crystal chemistry to evaluate the stability range, temperature of formation and the nature of parental magma from which these pyroxenes crystallized.

TABLE 2

Cation percentage of Sukinda orthopyroxenes

Serial No.	1	2	3	4	5
Sample No.:	Ex	B124	B123	B68	M434
Si^{+4}	49.62	49.23	57.79	57.66	48.98
Al^{+3}	0.88	0.60	0.74	0.62	1.35
Fe° (Total)	8.42	8.32	7.02	7.27	9.52
Mg^{+2}	40.17	41.23	33.67	33.83	39.05
Ca^{+2}	0.86	0.58	0.73	0.55	1.01
Na^{+1}	trace	trace	0.02	0.05	0.02
K^{+1}	0.04	0.04	0.03	0.03	0.11
Ti^{+4}	trace	trace	trace	trace	trace
Total	100.00	100.00	100.00	100.00	100.00
En ratio:	82.83	83.20	82.74	82.31	80.38

A comparison of the lime contents of Sukinda ultramafites with those of Ca-poor pyroxenes from basaltic parent magma and ultramafic 'magmas' as given by HESS [1960, p. 32, Table 5] is made in Table 3.

TABLE 3

CaO content in the orthopyroxenes of different parentage

	Average CaO (wt %)	Range CaO (wt %)
Orthopyroxene (Sukinda)	0.60	0.43—0.76
Basaltic parentage inverted pigeonite or pigeonite	0.31	3.8 —5.1
Ultramafic parentage orthopyroxenes	0.9	0.2 —1.9

Orthopyroxenes from nodules and intrusive peridotites are considered to be low in Ca and are derived from Ca-deficient magma [HESS, op. cit.]. HESS gave a range of 1,35—1,93% CaO for pyroxene derived from basaltic magma and 0,23—1,95% CaO for those from ultramafic magma. Table 3 shows the affinity of the Sukinda ultramafics to the latter source.

HESS later [1963] pointed out that although 'Ultramafic' orthopyroxenes usually have low lime contents, slightly higher values might be attained by fractional crystallization and early separation of Ca-deficient olivine, thus enriching the residual magma in lime. However, the orthopyroxenes from garnet — peridotites, quoted by O'HARA and MERCY [1963] are notably lime deficient.

The Ca-poor Sukinda orthopyroxenites indicate a peridotite magma source from which much less dunite fractions have been formed by crystallization fractionation than would be required for leaving a melt with greater amount of calcium for the formation of Ca-rich orthopyroxene and clinopyroxene exsolutions. Dunites, indeed occur only as a few minor bodies in this region. The orthopyroxenites cover far greater area than dunites. The proportions of spatial distribution of these two rocks have not, however, been determined by the author. The Ca-deficiency in orthopyroxenes, however, indicates that these pyroxenes were formed in a slow cooling condition, as otherwise, Ca-rich phases would form in a rapidly cooling stage.

ATLAS [1952] in a study of the synthetic system $MgSiO_3$—$CaMgSi_2O_3$ found that the amount of lime in enstatite varies with temperature as in Table 4.

TABLE 4

Ca atoms in enstatites and the temperature of formation

T°C	Number of Ca atoms (per unit cell) on the basis of 6 oxygens
1100°	0.115
1000°	0.050
700°	0.030

In the Sukinda enstatites the number of Ca-atoms per unit cell varies from 0,02 to 0,03 (rather 0,016 to 0,029, vide Table 8) suggesting a temperature range of about 700°C and below. No evidence of contact effect due to the intrusion could be seen in the area.

In Sukinda enstatites lime increases with alumina (except in B68) as also observed in Lizard [GREEN, 1963]. This suggests that temperature may partly control the entry of alumina into pyroxene structure.

MINOR OXIDE ANALYSES

Trace element and minor oxide content of the Sukinda orthopyroxenes determined by X-ray fluorescence are given in Table 5. Nickel, chromium and manganese are significantly higher in the relatively low alumina orthopyroxenes than in the high alumina ones. The range (in weight percent) of the minor oxides of the Sukinda

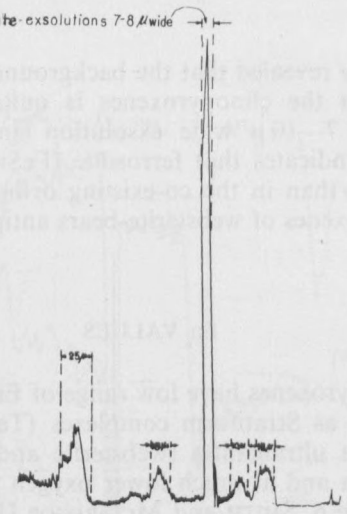

Fig. 3. Electron microprobe scanning for Cr over bronzite in enstatite.

enstatites are compared with those from other sources (Table 5) and it is found that these percentages cover a wide range but differ conclusively from those of the garnet — peridotite sources which contain notably less Cr_2O_3 and NiO. The orthopyroxenes from the garnet-peridotites, analyzed by O'HARA and MERCY [1963], were collected from Norway and the kimberlite pipes of South Africa. Other non-garnetiferous ultrabasic rocks occurring in the pipes contain slightly greater amount of Cr_2O_3 (0,2—0,6%). Pulverized samples of enstatite were also analyzed by the author for the estimation of trace mercury using the mercury vapour absorption meter at a set-up described by MITRA [1970]*. In the treatment 300 mA at the induction heater was used and the trace amount of mercury observed to range between 0,002 to 0,01 ppm (aprox.).

* This was done by the author when the instrument was handled by the author for the geochemical investigation for the base-metal mineralization between the two granites at Dartmoor and Bodminmoor) in SW England [MITRA and WEBB, 1967].

TABLE 5

Trace element content of Sukinda orthopyroxenes

	Cr_2O_3	TiO_2	MnO	NiO	References
Sukinda	0.04—0.8	0.001—0.2	0.01—0.1	0.1—0.25	Author
Lizard	0.4—0.7	0.2—0.4	0.1—0.2	n. d.	GREEN [1963]
Nodules	0.3—0.9	0.02—0.3	0.1—0.2	0.5—0.1	ROSS *et al.*, 1959.
Alpine type peridotites	0.6—0.8	0.02—0.2	0.1	0.1—0.2	ROSS *et al.*, 1959.
Garnet peridotite	0.02—0.2	0.05—0.1	0.1—0.2	0.003—0.005	O'HARA and MERCY, 1963.

Electron-probe study revealed that the background for chromium in the orthopyroxenes as well as in the clinopyroxenes is quite high. The orthopyroxenes (bronzites) show about 7—10 μ wide exsolution lamellae of chromite *(Fig. 3)*. Microprobe study also indicates that ferrosilite ($FeSiO_3$) molecules are more prevalent in clinopyroxenes than in the co-existing orthopyroxenes *(Fig. 4)*, although Fe in diopsidic clinopyroxenes of websterite bears antipathetic relation with calcium *(Fig. 5)*.

En VALUES

The Sukinda orthopyroxenes have low range of En values (80—83%) compared to many Alpine as well as Stratiform complexes (Table 6). These low En values suggest that the Sukinda ultramafites (websterite and enstatites) were crystallized in a nearly dry condition and at much lower oxygen pressure (partial) than in the other cases cited in Table 6. SMITH and MCGREGOR [1960] describe high En orthopyroxenes from the Mount Albert Complex as occurring in areas of high serpentinization and suggest that during crystallization increase in water pressure has

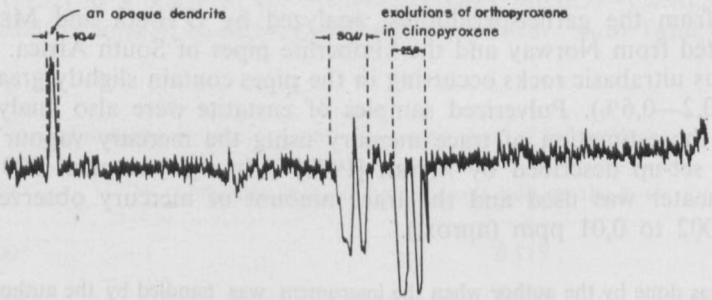

Fig. 4. Electron probe scanning for Fe over co-existing clinopyroxenes and orthopyroxenes.

increased partial oxygen pressure in these areas resulting in more Mg-rich orthopyroxenes. No evidence for increasing En in the serpentinized areas, in the southern region near the Mahagiri, could be traced by the author (analyses 4 and 5). The samples M 434 and B 68 were collected from the southwestern part of the map near Mahagiri, where serpentinized and schist bands occur in association with these ultrabasics. An analysis of the serpentinized pyroxenite (with relict grains of orthopyroxene; sample no. P 125, collected from 1 km. S. W. of Purnapani village) is presented in Table 7 on water free basis for comparison with those of orthopyroxenes of this area (Table 1). This evidently indicates that the serpentinized body represented by P 125 was enstatitites and was also formed at a low oxygen pressure. Unfortunately other samples of this locality could not be analyzed.

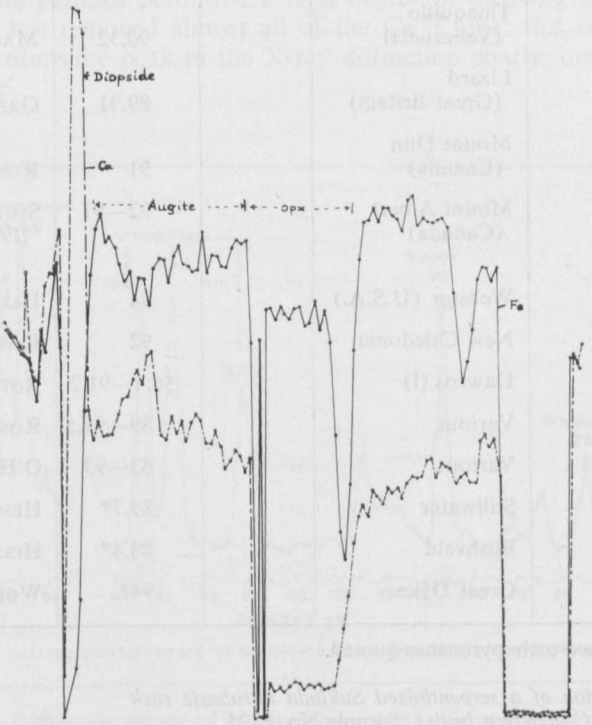

Fig. 5. Geoscan traverse for Ca and Fe over diopside with exsolved orthopyroxenes.

The serpentinization of the second phase intrusives, exposing in the SW part of the area was, indeed, later than the main period of intrusion [MITRA, 1960] and the magmatic change over to serpentine in this case were very incipient for consideration.

For comparison the Fe contents of olivines occurring in the associated rocks viz., harzburgite, peridotite, dunite, iddingsite rock (with olivine) and chilled gabbros, as already reported by the author elsewhere [MITRA, 1970], are presented in Table 6 along with those from other environments of the world. The Fe content of olivines varies between 81% to 93% in the ultramafites of the present area, corresponding to the En range of the orthopyroxenes 80—83%.

TABLE 6

Comparison of mol. per cent of En in orthopyroxenes from different regions

Type	Area	Sample No.	En value	References
	Sukinda Orissa	Ex	82.83	Author
		B124	83.20	
		B123	82.74	
		B68	82.31	
		M434	80.38	
Alpine	Tinaquillo (Venezuela)		90.32	MACKENZIE [1960]
	Lizard (Great Britain)		89.91	GREEN [1964]
	Mount Dun (Canada)		91	ROSS *et al.* [1954]
	Mount Albert (Canada)		92—97	SMITH and MCGREGOR [1960]
	Webster (U.S.A.)		94	HESS [1952]
	New Caledonia		92	ROSS *et al.* [1954]
	Dawros (I)		56.4—91.2	ROTHSTEIN [1958]
Nodules in Basalt	Various		89—91.5	ROSS *et al.* [1964]
Garnet peridotite	Various		83—93	O'HARA [1963]
	Stillwater		89.7*	HESS [1956]
Layered Complexes	Bushveld		88.4*	HESS [1952]
	Great Dyke		94*	WORST [1958]

* Earliest formed orthopyroxenes quoted.

TABLE 7

Composition of a serpentinized Sukinda ultrabasic rock (water-free basis) Sample No. P125

	SiO_2	56.01%
	Al_2O_3	0.55
(Total iron as)	Fe_2O_3	6.30
	MgO	36.68
	CaO	0.43
	Na_2O	Trace
	K_2O	0.03
	Total	100.00%

One important consideration of the other aspect of the enstatite compositions is their low alumina content, which is generally below 1%. Some cases, having $Al_2O_3 > 1\%$, however, led the author to postulate a possibility of formation of some isolated chemically heterogeneous pockets or lenses of nearing garnet-peridotite composition or some minor layers with higher Ca, Al and Fe content in the magma.

CRYSTAL CHEMISTRY

Investigations of the orthopyroxenes of this area reveal characteristics of slow cooling with nearly complete removal of Ca in diopsidic clinopyroxenes which occur occasionally as thin exsolution lamellae or as blebs.

Slow cooling perhaps permitted a high degree of ordering and the exsolution of the lamellae has removed almost all of the Ca^{+2} ions; this is indicated by the absence of any diopsidic peak in the X-ray diffraction charts, one of which is presented in *Fig. 6*.

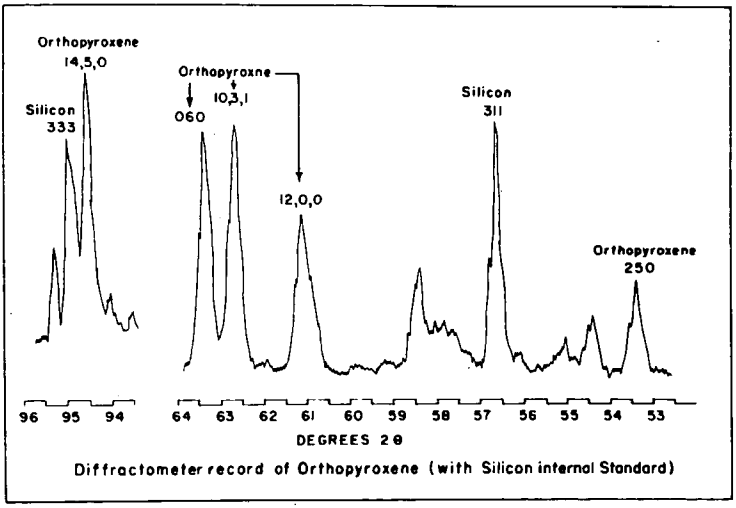

Fig. 6. Diffraction record of orthopyroxene (with silicon internal standard).

The diffraction study of nearly pure orthopyroxenites collected from south of Purnapani village was carried out by Philips high-angle diffractometer. The specimens were finely ground and mixed with pure silicon (as internal standard) and examined as smear mounts. Scans were made from 46°—65° 2Θ, 70°—77° 2Θ and 85°—96° 2Θ. Ni-filtered CuK_α radiation was used with scan speed of 1/8°/min. and chart speed 200 mm. and rate meter $\times 8$. Pulse height discriminator was used to increase peak to background ratios. The 2Θ values were corrected by the use of silicon peaks. Average of three repetitions was used. The 2Θ's (and d-spacings, thus obtained) were accurately measured and were used for the determination of cell parameters using Cohen crystallographic computer programmes for lattice parameter refinement and for calculating expected line position.

In the programme, written in FORTRAN and using Cohen's method (see N. V. COHEN, Rev. Sci. Inst., *6*, [1935] 68, and ibid *7*, [1936], 155), the lines were weighted as 1/2 $\sin^2 2\Theta$ (J. B. HESS, Acta Cryst., *4*, [1951], 209). For refinement of the parameters NELSON—RILEY extrapolation function $\frac{\cos^2\Theta}{\sin\Theta} + \frac{\cos^2\Theta}{\Theta}$ was used, the alternative diffractometer off-axis function ($\cos\Theta \cot\Theta$) was also available. The output from the programme was a list of indexed lines with observed and calculated "*d*" and $\sin^2\Theta$ values for each and the calculated lattice-parameters and their standard deviations; the slope of the extrapolation function and the sum of $(\sin^2\Theta_{calc} - \sin^2\Theta_{obs})^2$ were also printed. The programme rejected lines which were not in agreement with the majority.

An example of the output of the work is shown in Appendix I. The cell parameters shown are:

$a = 8{,}84968 \pm 0{,}00511$ (S.D.) Å
$b = 18{,}20741 \pm 0{,}01140$ (S.D.) Å
$c = 5{,}19721 \pm 0{,}00469$ (S.D.) Å.

Since the indices of reflection were determined from A.S.T.M., which used the space group $D_{2H}^{15} - Pcab$, the *b* and *a* values are interchanged when the space group is taken as Pbcs, as used in the DEER, HOWIE and ZUSSMAN [1963, 2, p. 9].

Some parameters were also manually determined by following RAMBERG and DEVORE [1951]. The a_0 and b_0 cell dimensions were measured initially on 12, 0, 0 and 0, 6, 0 and refined by reference to 14, 5, 0 and 250. The 2Θ positions of these reflections are shown in *Fig. 6*. The c_0 parameter was measured from the weak 004 reflection (73° 2Θ) after HOWIE [1963]. The 2Θ values were corrected by use of the silicon internal standard.

The chemical analyses of the orthopyroxenes (Table 1) have been recalculated to six oxygen atoms and the cations are grouped to *Z* and *WXY* positions (Table 8).

TABLE 8

Ortopyroxene analyses recalculated to 6 oxigens basis

	Serial No.	1	2	3	4	5
	Sample No.	Ex	B124	B123	B68	M434
Z	Si^{+4}	1.9992	1.9231	1.9905	1.9865	1.9803
	Al^{+3}	0.0008	0.0218	0.0095	0.0135	0.0197
W	Al^{+3}	0.0149	—	0.0069	0.0002	0.0052
X	Fe^{+2}	0.0853	0.1636	0.0804	0.0807	0.0968
Y	Mg	1.8681	1.8587	1.8427	1.8537	1.8242
	Ti					
	Ca	0.0346	0.0158	0.0240	0.0183	0.0289
	Na			0.0016	0.0058	0.0016
	K	0.0004	0.0012	0.0012	0.0026	0.0060

According to the general formula of pyroxenes as

$(W)_{1-p}(X, Y)_{1+p}Z_2O_6$

where $W = Ca^{+2}, Na^{+1}$

$X = Mg^{+2}, Fe^{+2}, Mn^{+2}, Ni^{+2}$

$Y = Al^{+3}, Fe^{+3}, Cr^{+3}, Ti^{+4}$

$Z = Si^{+4}, Al^{+4}$.

The orthopyroxene series has $p \simeq 1$ and the amount of trivalent ion in these should be small. The general series Enstatite—Orthoferrosilite has ideally the formula as $(Mg, Fe^{+2})_2 Si_2O_6$.

There is no reason to suggest that other ion than Al^{+3} can enter into the Z position with Si^{+4}. The orthopyroxenes have therefore been divided into two groups WXY and Z and the alumina is distributed between the two in the following manner:

$$Z\,Al^{+3} = X\,Al^{+3} + Z\,Ti^{+4} + Cr^{+3} + Fe^{+3} - Na + K.$$

The recalculated analyses show a systematic substitution of Al^{+3} for Mg^{+2} and Si^{+4}. When calculated in this way the results, given in Table 8, show that there is certain deficiency in the Z group in some samples (B124). There may be solid solution along the orthopyroxene — olivine joint at high pressure [BOYD and ENGLAND 1960]. Similar cation deficiency is observed in the orthopyroxene analyses of peridotite nodules in basalt and alpine-type peridotites quoted by ROSS, FOSTER and MYERS [1954] and in those from Lizard enstatites [GREEN, 1964].

The analyses in general show greater substitution of aluminium for Z silicon than X magnesium.

Electron-probe investigation of bronzite revealed quite high chromium background *(Fig. 3)*. This may be due to distortions in the structure of orthopyroxene. Compounds of Cr^{+2} ions are relatively susceptible to JAHN—TELLER distortions and consequently are relatively enriched in orthopyroxene M_2 sites.

TABLE 9

Alumina in orthopyroxenes from different paragenesis

Paragenesis	Wt.% Al_2O_3	References
Metamorphic (mainly charnockite · granulite)	0.5 —0.95	HOWIE [1963]
Metamorphic (amphibole pyroxene-granulite)	1.25—3.12	SEN and REGE [1966]
Volcanics	0.5 —2.5	DEER, HOWIE and ZUSSMAN [1963, V. 2.]
Stratiform Complexes	0.5 —2.5	DEER, HOWIE and ZUSSMAN [1963, V. 2.]
Alpine-type peridotites	0.7 —6.5	ROSS, FOSTER, MYERS [1954] and GREEN [1964]
Nodules in basalt	2.1 —5.5	ROSS *et al.* [1954]
Garnet peridotite	1—2	O'HARA, MERCY [1963]
Alpine pyroxenit (Sukinda)	0.66—1.20	AUTHOR [1970]

A brief summary of alumina in orthopyroxenes from different parageneses is given in Table 9.

Orthopyroxenes from certain Alpine type peridotites contain relatively large amounts of alumina; in the Lizard orthopyroxenes it varies from 1 to 6,5% [GREEN, 1964]. Sukinda ultrabasics in comparison with other occurrences, mentioned in Table 9, have orthopyroxenes with the lowest range of Al_2O_3 content (0,66—1,20%). The variation of total alumina with the En ratio in Sukinda orthopyroxenes (Tables 1 and 2) is compared with those from various parageneses (*Fig. 7*).

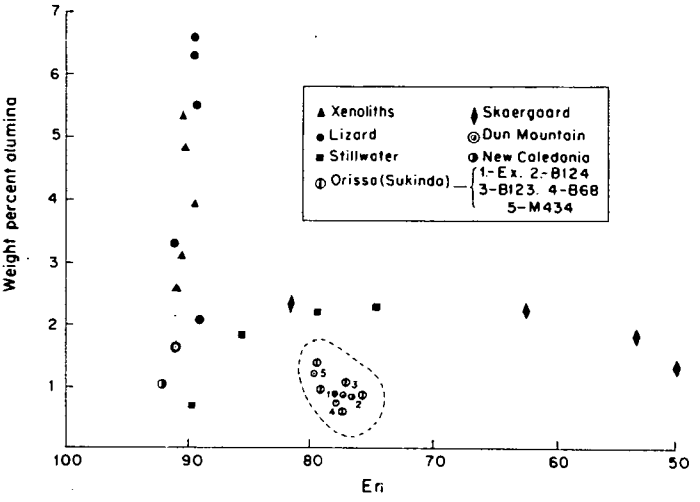

Fig. 7. Relation between weight per cent alumina and molecular per cent En in calcium-poor pyroxenes from plutonic igneous rocks $En = 100\ Mg/Mg + Fe^{2+} + Fe^{3+} + Mn$.

In the Ca-poor pyroxenes of Skaergaard sequence alumina is fairly constant but shows a tendency to decrease at the iron-rich end.

The aluminous orthopyroxenes from the nodules in basalt, Lizard, have very similar En ratios, but show a wide range of alumina content. Total alumina in the orthopyroxenes varies widely and is largely independent of the En ratio, although the greatest amount is found between En_{80} and En_{40}, as can be seen from the analyses quoted by HOWIE [1963]. The majority of these are from charnockites and granulites and it has been suggested that crystallization at high pressure is the condition for the formation of high alumina orthopyroxenes [BOYD and ENGLAND, 1960]. However, not all of them are aluminous. Alumina-rich orthopyroxenes can co-exist with Ca-poor garnet in granulite, free from clinopyroxenes [O'HARA, 1963]: whilst the reverse is true of the majority of the alumina-poor pyroxenes. Orthopyroxenes between En_{80} and En_{40} more readily accommodate alumina than either more magnesium or more iron-rich types [RAMBERG and DEVORE, 1951]. Although this may be partially true of the metamorphic orthopyroxenes the same does not apply for other parageneses.

Pressure may favour the reaction $MgMgSiSiO_6 \rightarrow MgAlAlSiO_6$, because of the resultant decrease in volume [HESS, 1952]. The system $MgSiO_3$—Al_2O_3 has been investigated by BOYD and ENGLAND [1960] who have shown that the maximum alumina substitution in enstatite at 1 bar is 5 p.c., but at 18,000 bars and a temperature of 1400°C up to 14 wt. p.c. alumina, and possibly 19 wt. p.c. can be accommodated in the enstatite structure. However, their experiments were made with synthetic enstatites free from $FeSiO_3$. HOWIE [1963, Table 3, No. B 20] has analyzed a hypersthene from a hornfels containing 7,2 wt.% Al_2O_3 and it is doubtful if this rock formed at high pressure. HESS [1952] suggested that enstatites from peridotite nodules in basalt may have been brought up from the mantle and their high alumina content is a result of pressure or high temperature of crystallization at depth.

On the other hand, garnet peridotites contain low alumina orthopyroxenes and these are considered to have originated at high pressure.

Thermodynamic considerations also suggest that the temperature of crystallization controls the amount of Al_2O_3 entering the pyroxene structure [BUERGER, 1948.]

CALCIUM IN WORLD ORTHOPYROXENES

The lime content of the analyzed Sukinda orthopyroxene varies from 0,43—0,76% and increases slightly with alumina *(Fig. 8)*. Local heterogeneity in the magma of this region, having pockets of higher $P-T$ phases of orthopyroxenes (as partially represented by M 434) is postulated by the author.

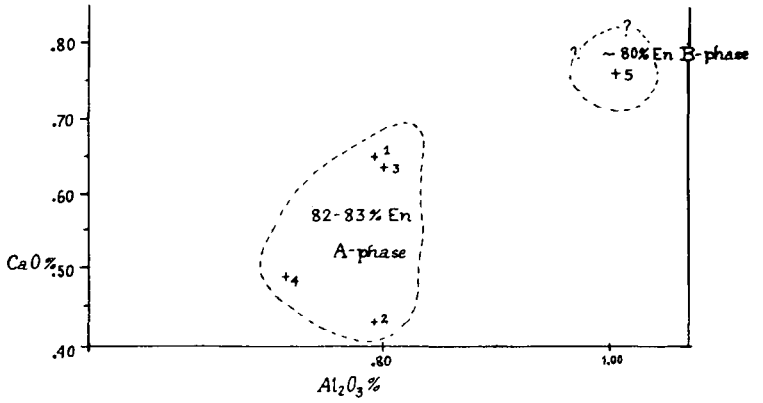

Fig. 8. Plot of CaO% vs. Al_2O_3% in orthopyroxenes. A change in magmatic condition during the crystallization of B-phase (~80% En content) from the possibly earlier A-phase (82—83% En content) formation.

The orthopyroxenes of Sukinda rarely contain fine exsolution lamellae of clinopyroxene, which also supports a peridotite source rather than basaltic. The lamellae, when present, are of the "Stillwater type" as defined by HESS [1960], and are not inverted pigeonites. Orthopyroxenes of Bushveld type have lamellae parallel to 100 [HESS and PHILLIPS, 1938].

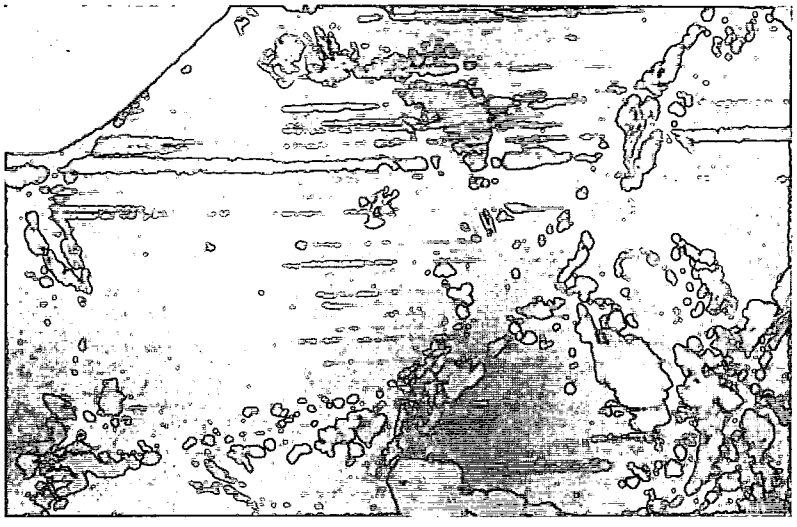

Fig. 9. Twinned orthopyroxene with very fine exsolutions of clinopyroxenes (x 250).

The 100 lamellae are not always attributed to exsolution of clinopyroxenes. The lamellae are due to translation in (100) accompanied by banding about (100). Optical studies of orthopyroxene from the Insizwa intrusion, E. GREENLAND indicated that the lamellar structure is due to multiple twinning about the *Z*-axis [BRUYNZEEL, 1957]. In the Sukinda orthopyroxenes, however, the lamellae, when present, are mostly in optical continuity. Interfaces with common structure are sites of minimal energy requiring unmixing to occur [BUERGER, 1948]. But their optical properties (*e. g.* greater birefringence than that of the host) leave no doubt regarding their exsolution nature. Moreover in serpentinized enstatites the exsolu-

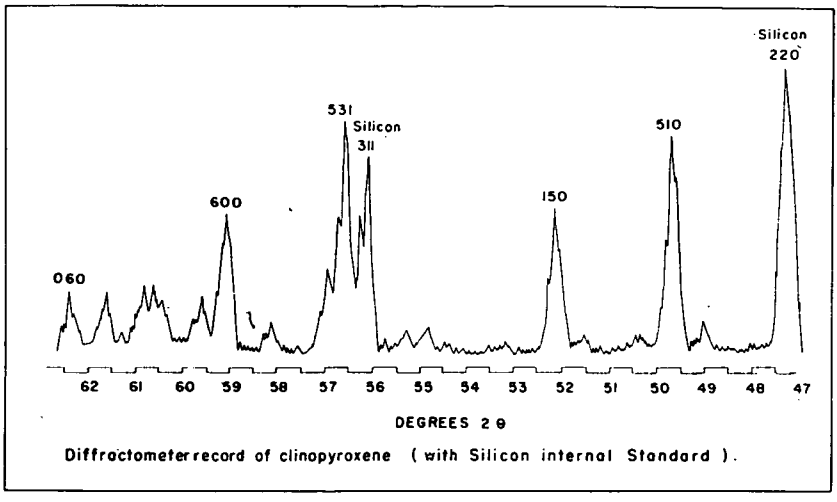

Fig. 10. Diffraction record of clinopyroxene (with silicon internal standard).

tion lamellae are frequently unaltered indicating that they have different compositions than the host *(Fig. 9)*.

Some electron-probe study for Ca and Fe *(Fig. 5)* revealed fine bands of diopside in augitic clinopyroxene co-existing with orthopyroxenes. In places fine (20—30 μ) exsolution of orthopyroxenes in clinopyroxene is also observed *(Fig. 4)*. In most cases background noise due to Cr was quite high. The species of the clinopyroxenes identified are predominantly augite and diopside. These were often determined from the X-ray diffraction chart, a relevant part of the 2Θ range etc. used, is presented in *Fig. 10*.

Orthopyroxenes of Bushveld type crystallized below the inversion temperature of orthorhombic to monoclinic pyroxenes (approx. 1140 °C) and the exsolution was due to slow cooling; whereas the poorly developed lamellae in orthopyroxenes in Sukinda suggest that these were formed by faster cooling of the crystallizing peridotite magma.

The coef. of correlation (γ) between Al_2O_3 and CaO is 0,7509 and the regression equation for these is

$$Al_2O_3 = 0{,}1458 + 0{,}011721\ CaO.$$

CONCLUSION

The occurrence of dunite and pyroxene-bearing peridotite viz., harzburgite websterite, wehrlite and lherzolite in the present area suggests that crystallization of these took place from differential layers of their own bulk composition in an Al_2O_3-free ultrabasic magma.

The implication of lime content in the enstatites of Sukinda lies in shifting the pointer towards an ultramafic (peridotite) magma indicating it as the parent magma in the present area of the Eastern Ghat region of Eastern India. Search of literature has not brought out any experimental evidence that liquids close to orthopyroxenite in composition can be produced by partial fusion of peridotites in any pressure-temperature environment. It is therefore concluded that the rocks that fused to produce the Sukinda magma were compositionally unlike any present day upper mantle magma genetic zones. The intrusive magma, however, could be contaminated with the primitive rocks, which might have changed the path of crystallization.

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ENSTATITE

PROGRAM COHEN CASE 12/1967/01
TWO THETA CORRECTION 0.000
REJECTED LINES. ERROR = 0.00400
NONE
REJECTED LINES. ERROR = 0.00360
NONE
REJECTED LINES. ERROR = 0.00320
NONE
REJECTED LINES. ERROR = 0.00280
NONE
REJECTED LINES. ERROR = 0.00240
NONE
REJECTED LINES. ERROR = 0.00200
NONE
REJECTED LINES. ERROR = 0.00160
NONE
REJECTED LINES. ERROR = 0.00120
NONE
REJECTED LINES. ERROR = 0.00080
NONE
LINE USED

Space Group S. G. D_{2h}^{15} – PcAB

H	K	L	D OBS	D CALC	DELATA D	SIN SQ THETA OBS	CALC	DIFF
1	2	0	6.35271	6.34361	0.00910	0.01985	0.01991	—0.00006
2	0	0	4.41401	4.42390	—0.00990	0.04112	0.04094	0.00018
2	1	1	3.30579	3.31240	—0.00661	0.07332	0.07302	0.00029
2	4	0	3.17029	3.17233	—0.00203	0.07972	0.07961	0.00010
2	2	1	3.17029	3.15925	0.01104	0.07972	0.08027	—0.00056
2	3	1	2.94410	2.94531	—0.00121	0.09244	0.09236	0.00008
1	6	0	2.87348	2.87013	0.00335	0.09704	0.09726	—0.00023
1	5	1	2.82834	2.82577	0.00257	0.10016	0.10034	—0.00018
2	4	1	2.70822	2.70772	0.00050	0.10924	0.10928	—0.00004
3	1	1	2.53816	2.54008	—0.00191	0'12437	0.12418	0.00019
0	2	2	2.49773	2.49853	—0.00080	0.12843	0.12835	0.00008
3	4	0	2.47412	2.47524	—0.00112	0.13089	0.13077	0.00012
2	5	1	2.47412	2.47276	0.00136	0.13089	0.13103	—0.00014
3	6	1	1.95823	1.95900	—0.00077	0.20894	0.20878	0.00016
2	9	1	1.73291	1.73428	—0.00138	0.26681	0.26638	0.00043
5	5	1	1.52284	1.52199	0.00085	0.34549	0.34588	—0.00039

PROGRAM COHEN CASE 12196701
NELSON—REILEY EXTRAPOLATION
DIFFRACTOMETER COS THETA X COT THETA EXTRAPOLATION
WEIGHTING FUNCTION COSEC SQUARED TWO THETA

PARAMETER S. DEV

A = 8.84968 ± 0.00511 Å
B = 18.20741 ± 0.01140 Å
C = 5.19721 ± 0.00469 Å

QEW = 9.68E-07
SLOPE = 8.91E-05 3.94E-04

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